# Remote Ultralow-Light Imaging

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Much of scientific research depends on the ability to observe objects and phenomena that are invisible to the naked eye because of their small size, high speed, distance, or shielding. Many technologies exist to aid our observations of such objects, and these technologies are constantly advancing to capture more challenging phenomena with greater accuracy and precision.

One area in which the technology has advanced significantly in the last few decades is low-light imaging. Intensified imaging techniques have been in use for many years in applications such as night vision. These techniques allow us to see in the dark, but they provide only two-dimensional views and they do not address the problem of shielded objects. To address these shortfalls, we have developed a remote ultra-low light imaging (RULLI) sensor technology that simultaneously measures the position and absolute time of arrival of individual photons to provide data that are literally three-dimensional (3-D). Our RULLI technique allows us to create 3-D images of objects in low-light conditions—even objects that are moving or, in some cases, shielded from plain sight.

RULLI uses a microchannel plate/crossed delay line (MCP/CDL) detector and pulse absolute timing (PAT) electronics. The MCP/CDL detector is a hermetically sealed vacuum tube that contains a transparent window coated on the inside with visible-light-sensitive photocathode material, a Z-stack of three MCPs, and a CDL readout. Figure 1 shows how the MCP/CDL converts photons into electrical pulses. An active illumination system with known timing characteristics, such as a laser light pulse, is used to illuminate the object, and the returned photons are detected. An incident photon reflects from the object being imaged through the tube window of

Fig. 1   The MCP/CDL detector shown in this diagram converts photons into electrical pulses to record their precise arrival times. Using MDP/CDL technology combined with PAT electronics, our RULLI technique is able to acquire optical data at the single-photon level.

Photon

Photocathode

Photoelectrons

MCP Z-Stack

10^7 electron charge cloud

CDL readout

Y2

Y1

X1

X2
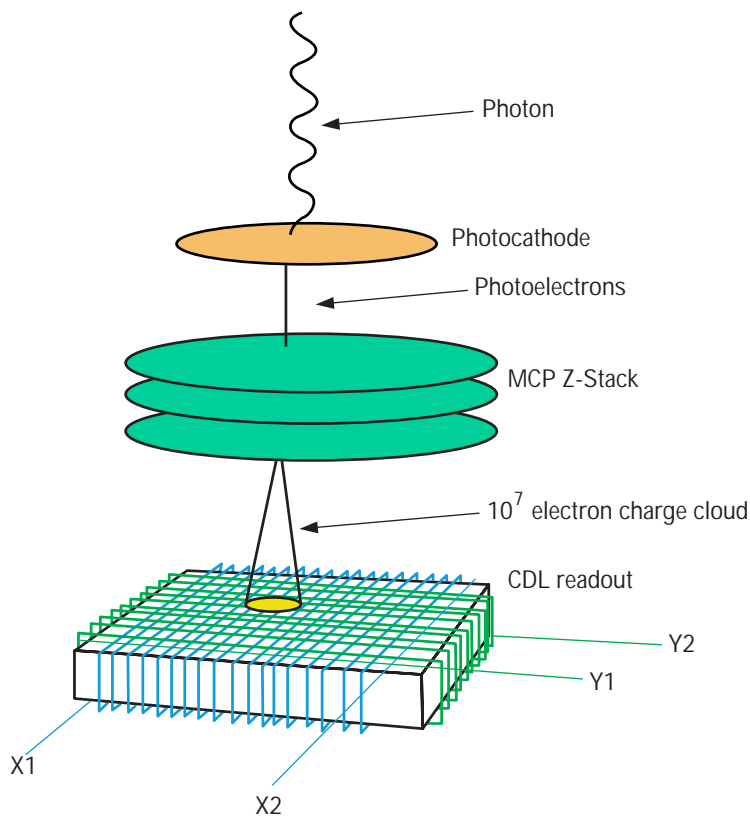
the detector, where it strikes the photocathode material. With a finite probability—the quantum efficiency—the photon excites an electron, which leaves the photocathode surface. A bias voltage between the photocathode and the front of the detector's MCP stack attracts the photoelectron towards the first MCP, which consists of many tiny pores. A moderately high voltage, typically above 3,000 V (in vacuum), is applied between the front and the back of the MCP stack. Electrons propagating inside the pores rapidly multiply and avalanche, producing a charge cloud of around 10^7 electrons that is accelerated toward the layered CDLs.

The CDL readout consists of two wires in perpendicular helical windings, one outside of the other. These are supported by a common ceramic structure to fix their position. A ground plane is placed in the middle of the support structure. The charge cloud generated by a single photon event speeds toward and through the windings. Several delay lines interact with the charges, and the signal, after propagation through the windings, becomes a Gaussian-like electrical pulse presented at each of the two ends. With two layers of winding, each having two ends, we have four independent signals: X1, X2, Y1, and Y2.

Measuring the pulses' arrival times, we can reconstruct the position and arrival time of the initial photon event. This is accomplished using the PAT electronics, which is a fast and accurate timing technology that originated in the nuclear test program at Los Alamos. Each PAT board contains the analog and digital electronics to measure the pulse's arrival time relative to a stable clock. One key component of the PAT data acquisition system is a hybrid module known as the Time Interval Meter (TIM) circuit. The TIM measures the time interval between a start and stop signal with a resolution of 10 ps, an accuracy 20 ps for single pulse, and a deadtime of about 80 ns. The TIM uses a built-in constant fraction discriminator (CFD) triggering circuit to ensure that the signal is triggered at a fixed location of the pulse profile, relatively independent of the pulse amplitude. The digital output from the TIM is sent to fast digital electronics to collect, format, and record the data. Through custom algorithms, the position and absolute time of the incident photon event is calculated from the raw data.

To date, we have achieved the following performance in the laboratory: a full-width-half-maximum (FWHM) for a point source of 60 μm, and a timing accuracy for each photon of about 200 ps rms (root mean square) or 420 ps FWHM. We expect the current implementation to offer linear response up to a random count rate of about 10^6 counts per second before significant event degradation due to coincidence. In our literal 3-D imaging field and laboratory experiments (described below), the system had slightly degraded spatial and timing performance from the numbers above. As we continue to improve the system, we expect a point-source FWHM better than 30 μm, an absolute timing FWHM of about 100 ps, and a maximum count rate of 5×10^6 counts/second.
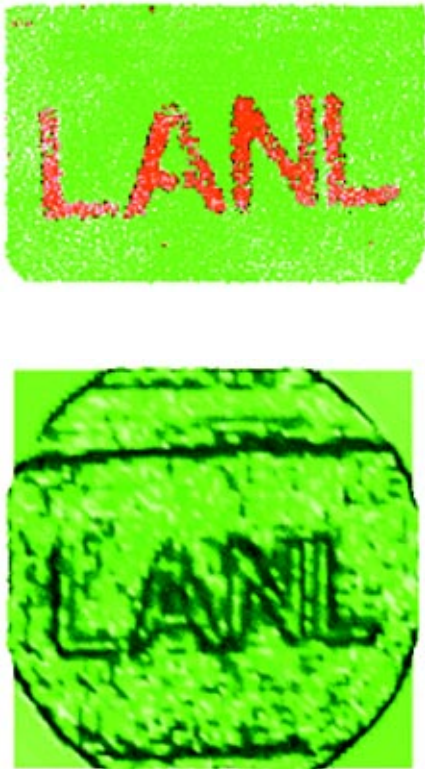
Fig. 2 These images, generated using the data from our laboratory experiment, clearly show that our RULLI technique resolved the 5-cm-high letters. The top image shows the data as a collection of points in 3-D space, with the closest points colored in red. The lower image shows the points as a surface under directed lighting. Our technique allows us to rotate and view these data from any angle.

The combination of MCP/CDL and PAT allows us to acquire optical data at the highest sensitivity possible: the single-photon level. By using the photon counting method to form the RULLI image we have no added readout noise. This means that the imaging limits of the system are dictated by the physics of the scene illumination, not by the detector readout. This level of sensitivity coupled with the timing precision allows the formation of high resolution images on moonless nights, even from moving platforms. Since we measure the CDL pulses at such high precision, we also have a very high resolution optical ranging system that requires the lowest of illumination power. In fact, the system is designed such that the illuminator returns to the detector, on average, one photon per incident pulse.

An end-to-end system with the capabilities needed for this literal 3-D imaging technique has been in operation since mid-1997. Using a commercial pulsed laser in combination with the RULLI technology, several experiments have been conducted under a variety of conditions.

To test RULLI's performance in a laboratory setting, we used a $30 \times 50 \times 5$-cm styrofoam block with 5-cm-thick styrofoam letters glued to the surface to spell out "LANL." The experiment was conducted in a dark laboratory at a distance of 7 m, and a pulsed laser triggered at 1.56 MHz was used for active illumination of the target. The laser was coupled to a 120-μm diameter, 7-m-long multimode optical fiber to achieve a more uniform illumination. The dark count over the entire detector area was about 600 counts per second, and the ambient light through the narrow band filter, including reflected light from two computer screens, contributed another 600 counts per second. The laser return accounted for about 1,200 counts per second. A number of data sets were collected with 240-second (4-minute) exposure times.

Using sophisticated information extraction algorithms, the extracted data were analyzed to separate the returned laser photons from the background photons. Background photons have a random arrival time, whereas the laser return photons have a known time signature that correlates with the laser pulse period. In this experiment, the culled data set contained about 288,000 photons compared to about 2,900 photons contributed from random background, giving a signal to background ratio of about 100:1. The culled data were then processed using a simple topography determination algorithm, and the images shown in Fig. 2 were generated. These images clearly show that we resolved the 5-cm height separation between the LANL letters and the solid styrofoam block.

In another experiment, we applied the RULLI technique to cloud studies. Because clouds are remote, change rapidly, and have structures from small to large scales, the existing tools to study real clouds experimentally have been very limited. We simulated a cloud with different scattering properties by mixing various amounts of fabric softener into a large fish tank filled with water. The 2- $\times$ 3- $\times$ 4-ft tank was observed with the MCP/CDL/PAT

sensor from a distance of 20 ft. A laser beam with sharp pulses at a regular rate of 1.6 MHz was focused close to the center of the field of view. Data were collected using several 60-second exposures.

Preliminary results of this experiment show the behaviors we expect from an optically thick cloud: Following an initial bright point-like spike from the prompt back-scattered photons at the air-tank interface, the photons spread out in spatial dimension and became dimmer. These late photons have undergone multiple scattering in the cloud and return towards the observer after long random walks, which displaces their exit position and angle. Detailed 3-D studies of these behaviors will significantly advance our understanding of clouds and other scattering media.

These experiments demonstrate that the RULLI technique offers a novel tool for imaging complex phenomena that could not be captured using previous techniques. The versatility of this measuring technique—the ability to detect individual photons and accurately measure their positions and arrival times—opens many avenues for gathering data on objects and phenomena that were previously unattainable. RULLI technology will be a solution for many research areas, including the study of small objects in low Earth-orbit, canopy density studies, astronomical imaging, optical brain imaging, and DNA studies. Our work will continue to improve this imaging technique and seek out novel applications. We anticipate that RULLI will reveal exciting phenomena in many areas where observation was previously impossible.